A journey in the history of Automated Driving

Christian Laugier

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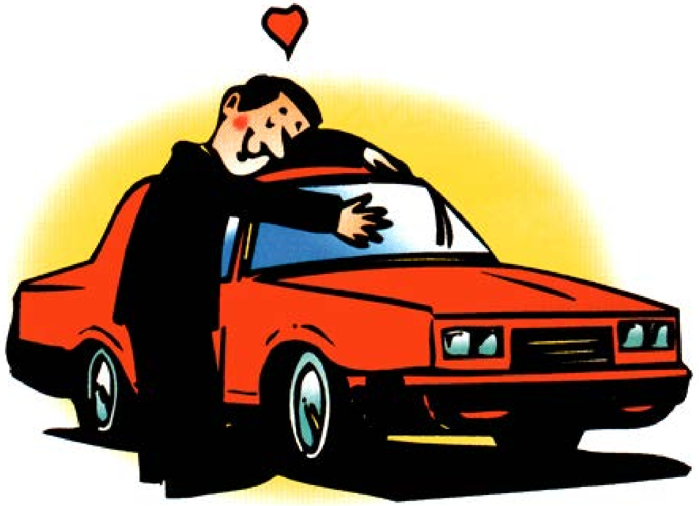
Invited Pioneer's Talk

IROS 2019, Macau, China, November 6th 2019



Contributions: *L. Rummelhard, A. Negre, N. Turro, J.A. David, J. Lussereau, T. Genevois, C. Tay Meng Keat, S. Lefevre, O. Erkent, D. Sierra-Gonzalez … and also numerous former PhD students and Postdocs*

Automobile & Human Mobility

A current Technological & Psychological breakthrough

*On-going change of the role & concept of **private car** in human society !*

Last century *=> Ownership & Feeling of Freedom*
Affective behaviors & Shown Social position
Driving pleasure ... but less and less true !

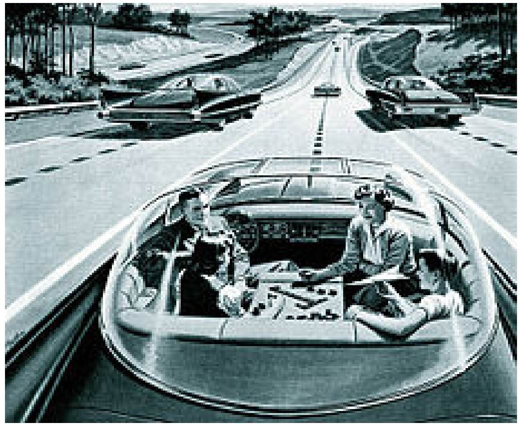
Next cars generation *=> Focus on* ***Technologies*** *for*
Safety & Comfort & Reduced Pollution
Driving Assistance v/s Autonomous Driving

Context of this recent evolution

- *Expected 3 Billions vehicles & 75% population in cities in 2050 => Current model not scalable !*
- *Accidents: ~1.2 Million fatalities/Year in the world => No more accepted by the human society !*
- *Driving safety & Nuisance issues (pollution, noise, traffic jam, parking …) are becoming* ***a major issue for Human Society & Governments & Industry***
- *Technology & Internet & Ecology & Economic issues progressively change* ***mobility habits*** *of people => Towards Less ownership & More shared mobility systems & Increased Autonomy … e.g. Uber, BlaBlaCar, Tesla Autopilot, Waymo…*

Early steps towards Autonomous Cars

❑ Early dream (1956):



"Central Power & Light Company" predict Autonomous Cars
…. on Electric super-highway

Advertorial: *"ELECTRICITY MAY BE THE DRIVER. One day your car may speed along an **electric super-highway**, its speed and steering automatically controlled by electronic devices embedded in the road. Highways will be made safe – by electricity! No traffic jams … no collisions … no driver fatigue"*

❑ EU: Some milestones in the 80's

VaMORs, Munchen Univ, 1986

- First autonomous vehicle on a road (mainly based on CV): VaMORs prototype, Dickmann, Munchen University, 1986
- EU project Prometheus (1987-95, ~750 M€), Largest R&D project on driverless cars (involving EU Industry & Universities)
  => Large public demonstration in Paris in 1994

EU: Some results in the 90's

Automatic parking, Inria, 1996
(low cost sensors, no map)

City Platooning & Concept of shared cars
Inria, 1997

Cycab concept (urban people mover)
Inria

https://en.wikipedia.org/wiki/Automatic parking

⇒ *One of the world's first experimental prototypes of automatic parallel parking was developed on an electric car Ligier at INRIA in the mid-1990s*[1][3] .

⇒ *The underlying technology has been adopted by major automobile manufacturers offering an automatic parking option in their cars today.*

⇒ *First commercial version of the automatic parallel parking concept on Toyota Lexus in 2010.*

[1] I. Paromtchik & C. Laugier, « Autonomous Parrallel Parking of a Nonholonomic Vehicle », IEEE Intelligent Vehicle Symposium 1996, Tokyo, Japan.

International Events & Projects *(A great impact, 1st decade 21st century)*

USA 2004 & 2006: Darpa Grand Challenges *(High speed & Off-road)*
=> Significant step towards Motion Autonomy… But still some uncontrolled behaviors in 2004

USA 2007: Darpa Urban Challenge *(97 km, 50 manned & unmanned vehicles, 35 teams)*
=> Impressive progress towards autonomous driving …. but still some collisions (Perception & Decision-making failures)

EU 2010: VIAC Intercontinental Autonomous Challenge *(A. Broggi, Parma)*
⇒ 13 000 km covered, 3 months race, leader + followers

USA 2011: Google Car project (1st large Industrial project on AD)
Fleet of 6 automated Toyota Prius, costly 3D lidar (dense mapping)
140 000 miles covered on California roads with occasional human interventions

Technology status & Ongoing challenges for AVs

- **Strong involvement of Car Industry & GAFA + Large media coverage + Increasing Governments supports**
- **An expected market of 515 B€ at horizon 2035** *(~17% world automobile market, Consulting agency AT Kearney, Dec 2017)*
- **But Legal & Regulation issues are still unclear … idem for Technologies Validation & Certification issues !**

=> Numerous experiments in real traffic conditions since 2010 (Disengagement reports => Insights on system maturity)

=> But still insufficient … Realistic Simulation & Formal methods are also under development (e.g. EU Enable-S3)

Millions of miles driven since 2010 (Google, Tesla, Waymo, Uber…)

Several benign & serious accidents in past few years

Safety is still not guaranteed !

Tesla Autopilot L2 with Radar & Mobileye/Intel
*Commercial ADAS product => **Tested by customers !!***

Numerous EU projects in last decades
Cybus, 3 months experiment, low speed
La Rochelle 2012 (France)

Dense 3D mapping & Numerous vehicles
10 years R&D, 8 millions km covered since 2010 & 25 000 km/day

Drive Me trials (Volvo, 2017)
- *100 Test Vehicles in Göteborg, 50 km, 70km/h*
- *No pedestrians & Separations between lanes*

"Self-Driving Taxi Service L3" testing in US *(Uber, Waymo)* & Singapore *(nuTonomy)*

⇒ ***Autonomous Mobility Service**, Numerous Sensors + "Safety driver" during testing (take over in case*

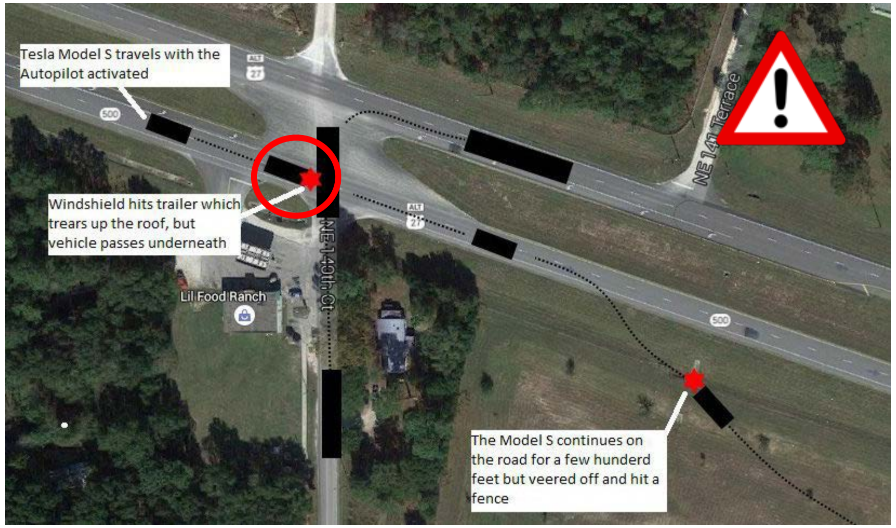
⇒ ***Uber:** System testing since 2017, Disengagement every 0.7 miles in 2017 (improved now)*

⇒ ***Waymo:** 1st US Self Driving Taxi Service launched in Phoenix in Dec 2018*

⇒ ***Disengagement reports provide insights on the technology maturity***

Fatal accidents involving AVs – *Perception failure*

❑ Tesla driver killed in a crash with Autopilot “level 2” active *(ADAS mode) – May 2016*



- ✓ ***The Autopilot <u>failed to detect</u> a white moving truck, with a brightly lit sky*** *(Camera Mobileye + Radar)*
- ✓ ***The human driver was not vigilant & didn’t took over***

❑ Self-driving Uber L3 vehicle killed a woman

=> First fatal crash involving a pedestrian

Temple, Arizona, March 2018

- ✓ ***Despite the presence of multiple sensors (lidars, cameras …), the <u>perception system failed to detect the pedestrian & didn’t disengaged</u>***
- ✓ ***The Safety Driver reacted too lately*** *(1s before the crash)*

AVs have to face two main challenges

Challenge 1: The need for **Robust**, **Self-diagnosing** & **Explainable** **Embedded Perception**

Video source: AutoPilot Review @ youtube.com

Video Scenario:

- *The Tesla perception system failed to detect the barriers blocking the left side route.*
- *The driver has to take over and steer the vehicle away from the blocked route (for avoiding the collision).*

AVs have to face two main challenges

Challenge 2: The need for **Understandable Driving Decisions** *(share the road with human drivers)*

Unfortunately Human drivers actions are determined by a complex set of interdependent factors difficult to model *(e.g. intentions, perception, emotions …)*

*⇒ **Predicting human driver behaviors is inherently uncertain***

*⇒ **AV have to reason about uncertain intentions of the surrounding vehicles***

Video source: The Telegraph

Video scenario (*Scene observed by the dash cam of a* ***bus*** *moving behind the Waymo AV)*

- ***Waymo AV*** *is blocked by an obstacle and it decides to execute a left lane change*
- *The* ***bus driver*** *misunderstood the Tesla's intention and didn't yield*
- *he two vehicles collided*

Perception & Decision-making requirements for AVs

Dynamic Scene Understanding & Navigation Decisions

Situation Awareness & Decision-making

⇒ *Sensing + Prior knowledge + Interpretation*
⇒ *Selecting appropriate Navigation strategy (planning & control)*

Embedded Perception & Decision-making for Safe Intentional Navigation

Dealing with unexpected events

Anticipation & Risk Prediction technologies
for avoiding upcoming collisions with "something"
=> *High reactivity & reflexive actions*
=> *Focus of Attention & Sensing*
=> *Collision Risk estimation + Avoidance strategy*

Main features

✓ Dynamic & Open Environments => *Real-time processing & Reactivity (several reasoning levels are required)*

✓ Incompleteness & Uncertainty => *Appropriate Model & Algorithms (probabilistic approaches)*

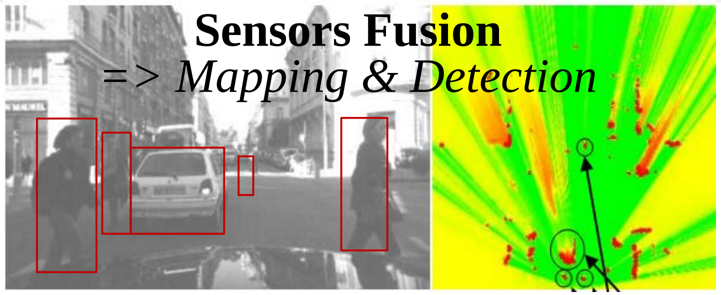
✓ Sensors limitations (no sensor is perfect) => *Multi-Sensors Fusion*

✓ Hardware / Software integration => *Satisfying Embedded constraints*

✓ Human in the loop (mixed traffic) => ***Human Aware Decision-making process (AI based technologies)***
Taking into account Interactions + Behaviors + Social rules (including traffic rules)

1st Paradigm : Embedded Bayesian Perception

Embedded Multi-Sensors Perception
⇒ ***Continuous monitoring of the dynamic environment***



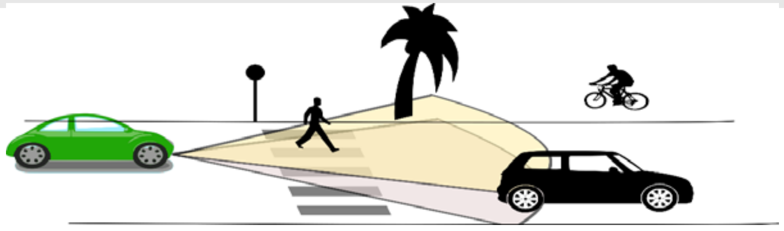
❑ Main challenges

- ✓ *Noisy data, Incompleteness, Dynamicity, Discrete measurements*
- ✓ ***Strong Embedded & Real time constraints***

❑ Our Approach: Embedded Bayesian Perception

- ✓ *Reasoning about* ***Uncertainty & Time window*** *(Past & Future events)*
- ✓ ***Improving robustness*** *using* ***Bayesian Sensors Fusion***
- ✓ ***Interpreting the dynamic scene*** *using* ***Contextual & Semantic*** *information*
- ✓ ***Software & Hardware integration*** *using GPU, Multicore, Microcontrollers…*

Bayesian Perception : Basic idea



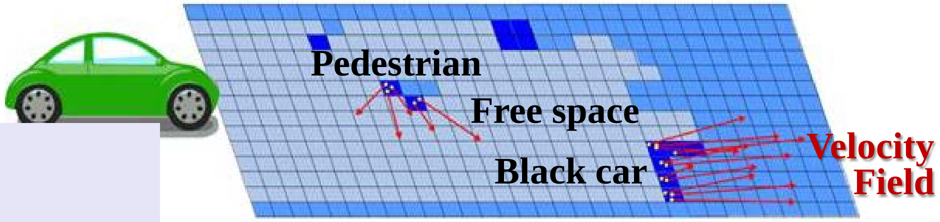
- **Multi-Sensors Observations**
  Lidar, Radar, Stereo camera, IMU …

Bayesian
Multi-Sensors Fusion

Real-time !

- **Probabilistic Environment Model including Dynamics**

P[o|Z,C] : ≃0 ≃0.5 ≃1



Concept of "Dynamic Probabilistic Grid + Bayesian Filtering"

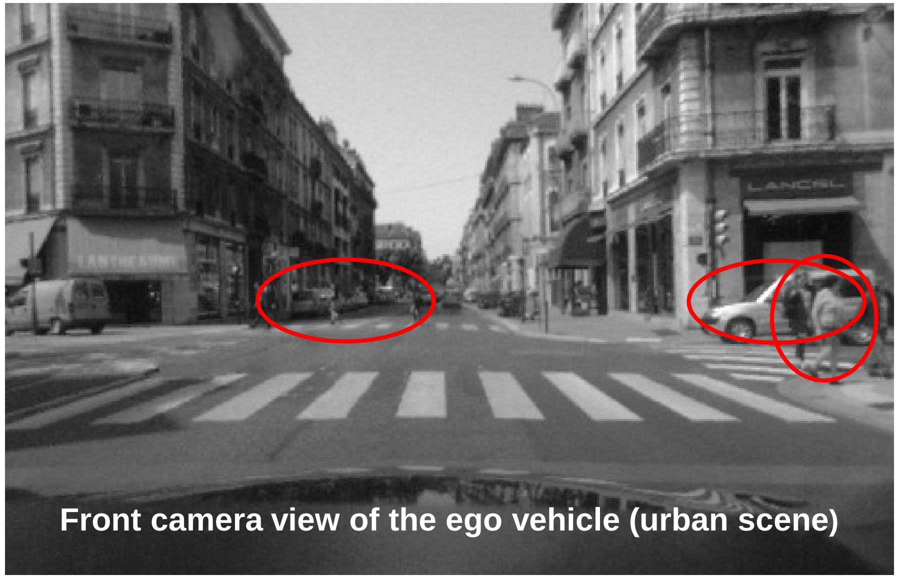
⇒ *Clear distinction between **Static** & **Dynamic** & **Free** components*
⇒ *Occupancy & Velocity probabilities*
⇒ *Designed for Highly Parallel Processing (to satisfy real-time constraints)*
⇒ *Includes Embedded Models for **<u>Motion Prediction & Collision Risk Assessment</u>***
⇒ *Patented technology & Industrial licenses 2018 (Toyota, Easymile)*

[PhD Thesis Coué 2005]
[Coué & Laugier IJRR 2005]
[Laugier et al ITSM 2011]
[Rummelhard et al ITSC 2015]
[Mooc uTOP 2015]

- **Main philosophy**
  Reasoning at the grid level as far as possible for both :
  - ***Improving Efficiency & Reactivity to unexpected events*** *=> Highly parallel processing & High frequency !*
  - ***Avoiding most of traditional object level processing problems*** *(e.g. detection errors, wrong data association…)*

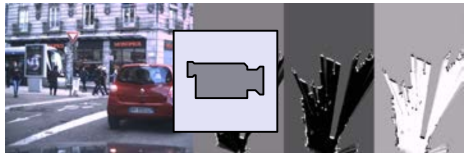
Dynamic Probabilistic Grid & Bayesian Filtering – *Main Features*

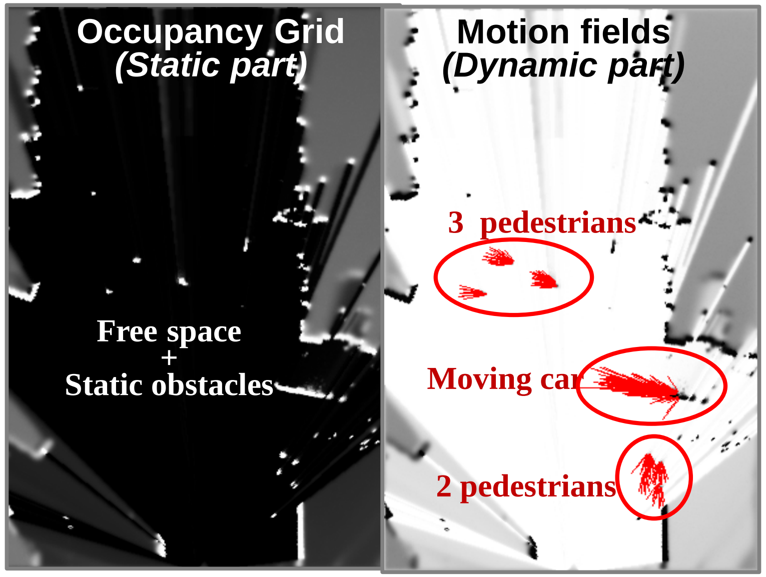
=> Exploiting the dynamic information for a better understanding of the scene



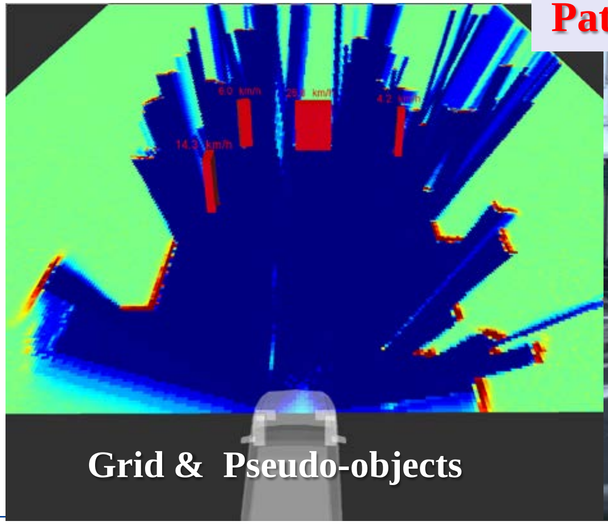
Sensors data fusion
+
Bayesian Filtering
+
Extracted Motion Fields

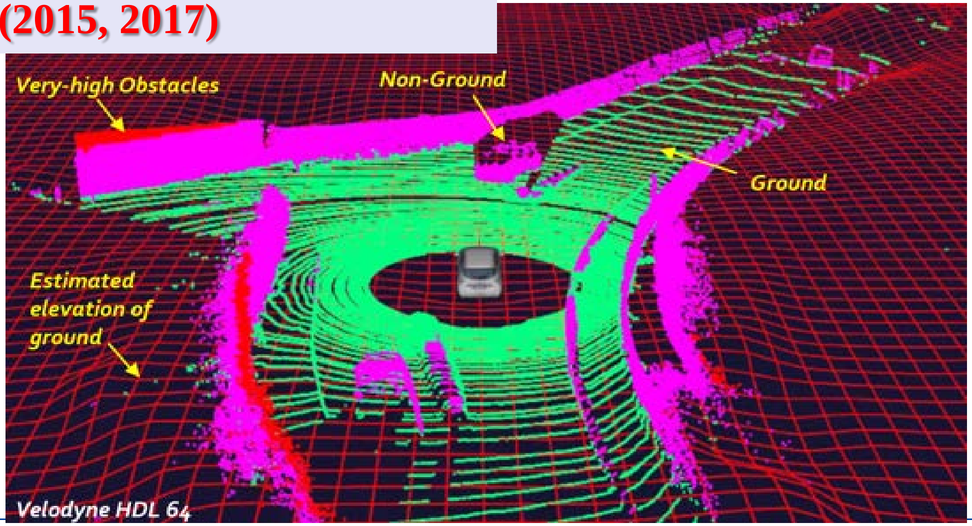
1st Embedded & Optimized version (HSBOF, patent 2014)





Patented Improvements & Implementations (2015, 2017)



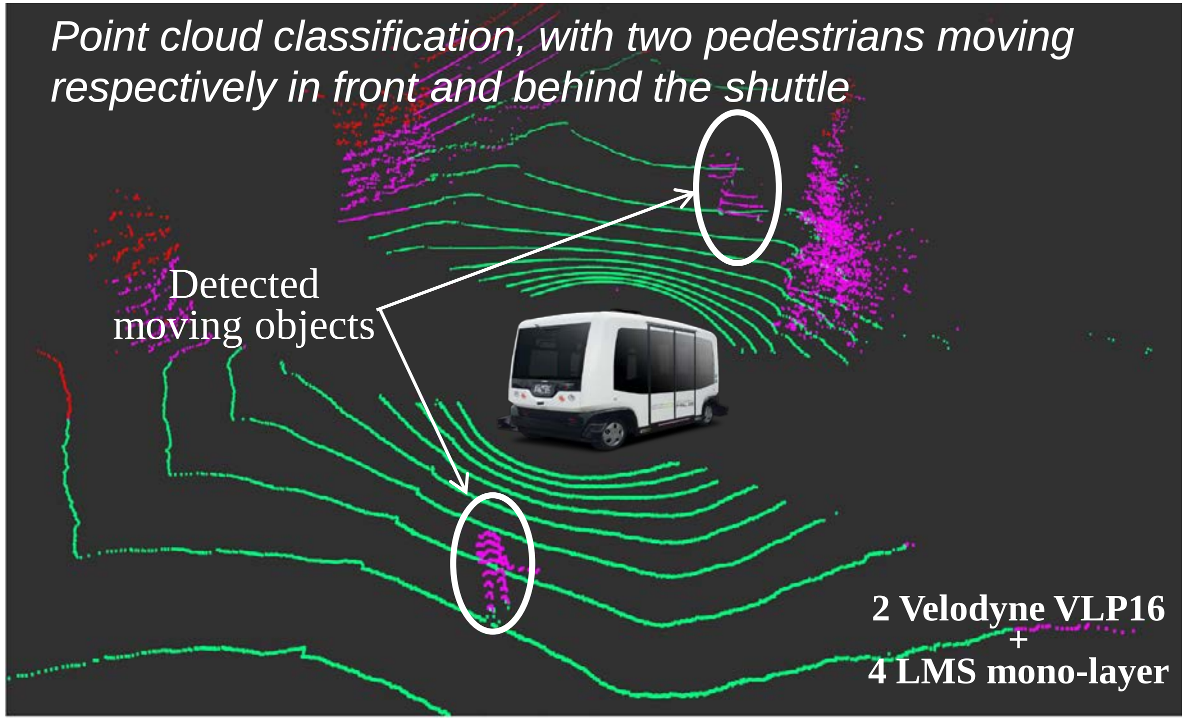


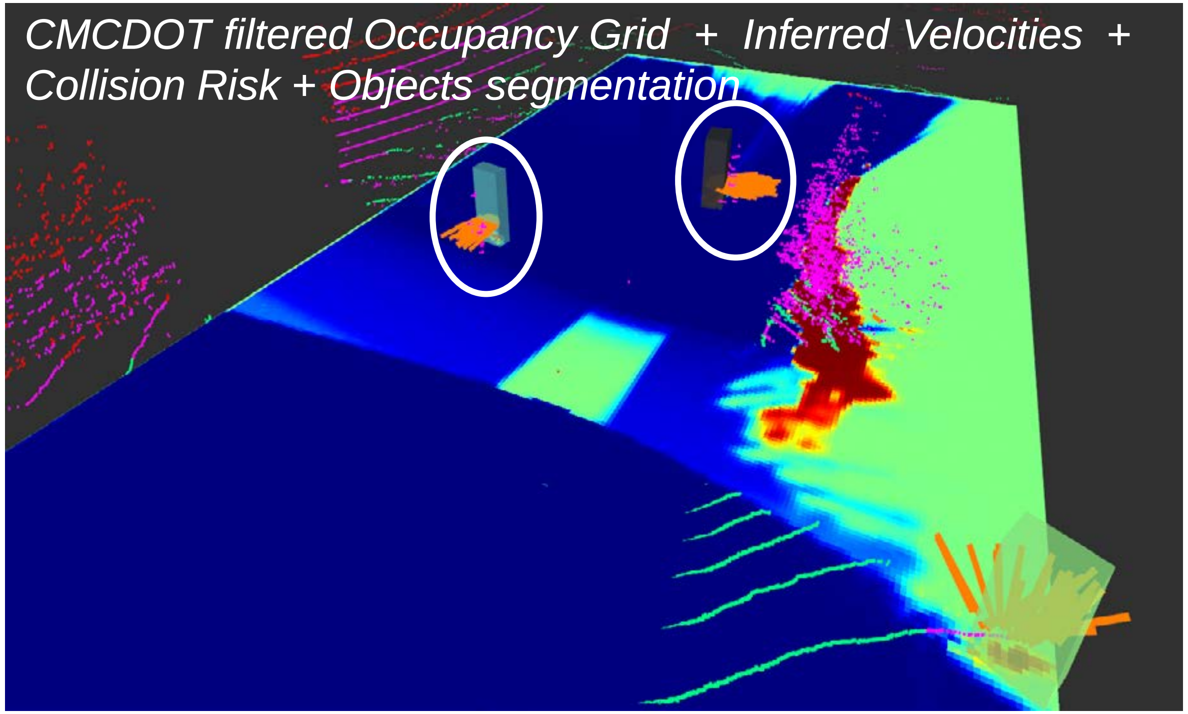
Detection & Tracking + Moving Objects Classification
=> CMCDOT 2015 (including a "Dense Occupancy Tracker")

Ground Estimation & Point Cloud Classification
(patent 2017)

System Integration on a Commercial Vehicle

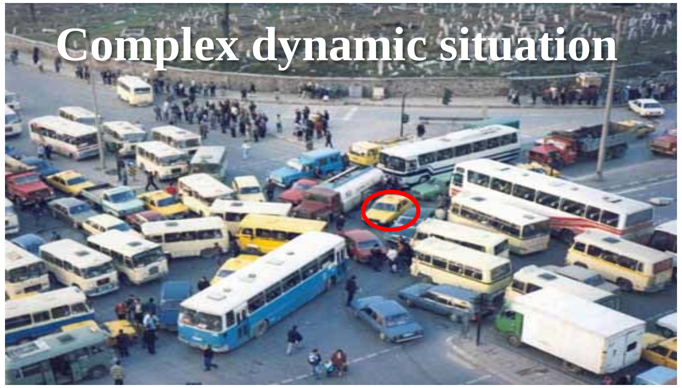
- **POC 2019: Complete system implemented on Nvidia TX1**, and easily connected to the shuttle system network *in a few days* (using ROS)
- **Shuttle sensors data** has been fused and processed in **real-time**, with a successful Detection & Characterization of the **Moving & Static Obstacles**
- **Full integration on a commercial product** under development with an industrial company (confidential)





2nd Paradigm: Collision Risk Assessment & Decision-making

=> *Decision-making for avoiding Pending & Future Collisions*



❑ Main challenges

Uncertainty, Partial Knowledge, World changes, Real time

Human in the loop + Unexpected events + Navigation Decision based on Perception & Prior Knowledge

❑ Approach: *Prediction + Risk Assessment + Bayesian Decision-making*

- ✓ *Reason about **Uncertainty & Contextual Knowledge** (using **History** & **Prediction**)*
- ✓ *Estimate **Probabilistic Collision Risk** at a given **time horizon t+δ** (δ = a few seconds)*
- ✓ *Make **Driving Decisions** by taking into account the **Predicted behavior** of all the observed surrounding traffic participants (cars, cycles, pedestrians …) & **Social / Traffic rules***

❑ Decision-making: *Two types of "collision risk" have to be considered*

- ✓ ***Short-term collision risk** => Imminent collisions with "something" (unclassified), time horizon <3s, conservative hypotheses*
- ✓ ***Long-term collision risk** => Future potential collisions, horizon >3s, Context + Semantics, Behavior models*

Concept 1: Short-term collision risk *(Basic idea)*

=> How to deal with unexpected & unclassified events (i.e. "something" is moving ahead) ?
=> Exploit previous observations for anticipating future objects motions & related potential future collision

Autonomous Vehicle (Cycab)

Parked Vehicle (occultation)

Pioneer Results (2005)

[PhD Thesis C. Coué 2004]
[Coué & Laugier & al IJRR 05]

Thanks to the prediction capability of the BOF technology, the Autonomous Vehicle "anticipates" the pedestrian motion and brakes *(even if the pedestrian is temporarily hidden by the parked vehicle)*

Short-term collision risk – *Main Features & Results*

=> Grid level & Conservative motion hypotheses (proximity perception)

Proximity perception: d <100m and t <5s
δ= 0.5 s => Precrash
δ= 1 s => Collision mitigation
δ > 1.5s => Warning / Emergency Braking

Main Features

- *Detect **"Upcoming potential Collisions"** a few seconds ahead (3-5s) **in the Dynamic Grid***
- *Risky situations are **both localized in <u>Space & Time</u>** (under conservative motion hypotheses)*
- *Resulting information is used for choosing the most appropriate Collision **Avoidance Maneuvers***

Experimental results

Urban street experiments
=> Reduce drastically False Alarms

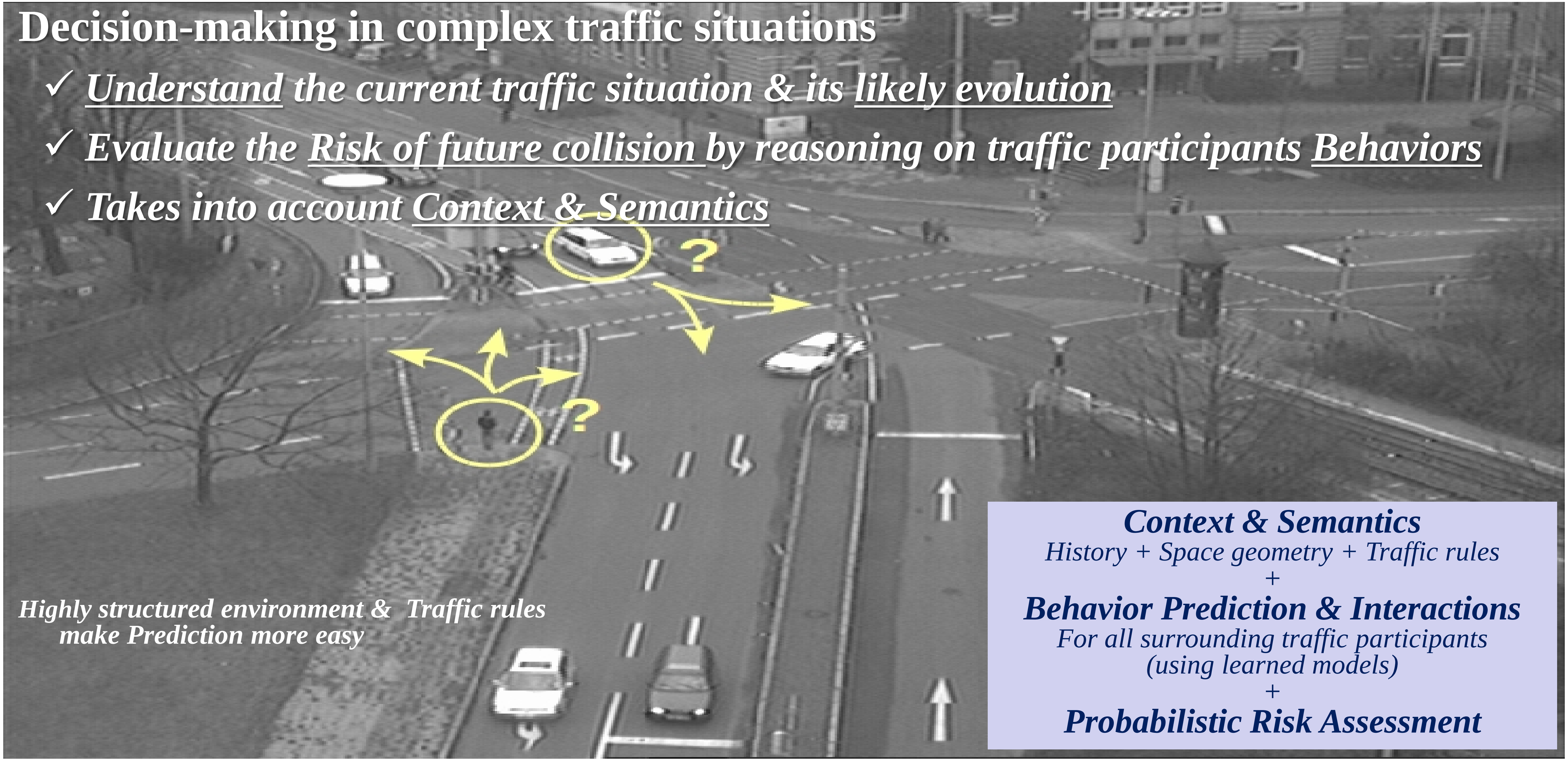
Crash scenario on test tracks
=> Almost all collisions predicted before the crash (0.5 – 3 s before)

Collision Risk Assessment *(video 0:45)*
- **Yellow** *=> time to collision: 3s*
- **Orange** *=> time to collision: 2s*
- **Red** *=> time to collision: 1s*

Concept 2: **Long-term Collision Risk** *(Object level)*

=> Increasing time horizon & complexity using ***Context & Semantics***

=> Key concepts: ***Behaviors Modeling & Prediction + Traffic Participants Interactions***



Decision-making in complex traffic situations

- ✓ *Understand the current traffic situation & its likely evolution*
- ✓ *Evaluate the Risk of future collision by reasoning on traffic participants Behaviors*
- ✓ *Takes into account Context & Semantics*

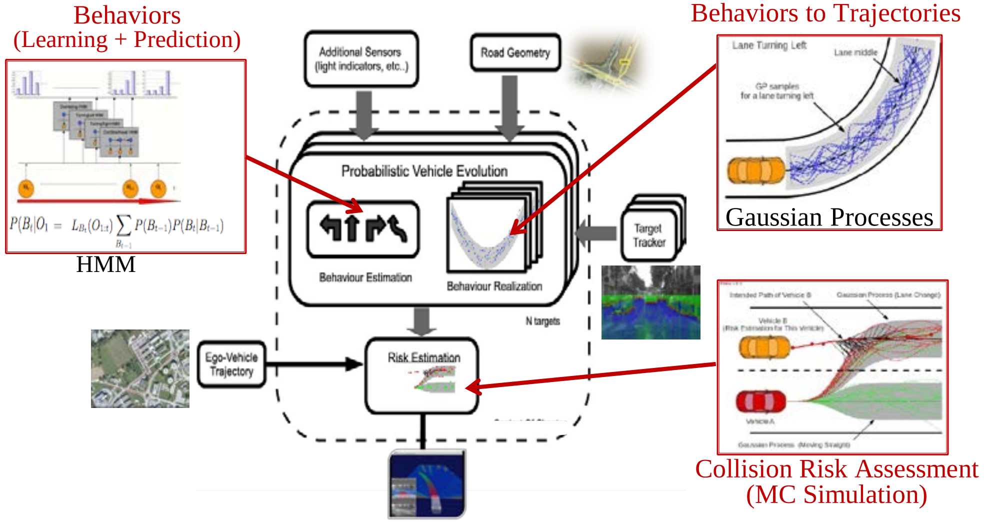
Highly structured environment & Traffic rules make Prediction more easy

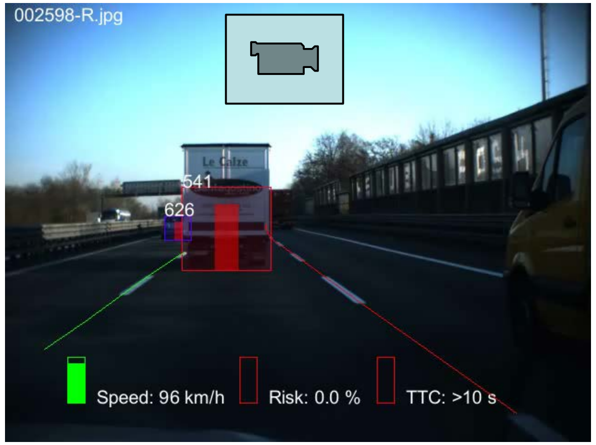
Context & Semantics
History + Space geometry + Traffic rules
+
Behavior Prediction & Interactions
For all surrounding traffic participants (using learned models)
+
Probabilistic Risk Assessment

Behavior-based Collision risk – *Main approaches & Results*

=> Increased time horizon & complexity + Reasoning on Behaviors & Interactions

❑ Trajectory prediction & Collision Risk *=> Patent 2010 (Inria, Toyota, Probayes)*

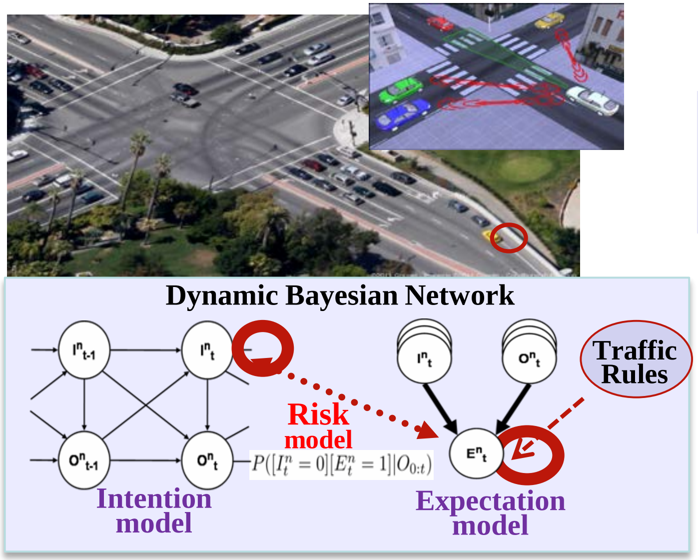




Courtesy Probayes

Cooperation still on-going (R&D contracts + PhD)

❑ Intention & Expectation *(Mixed Traffic & Interactions)* *=> Patents 2012 (Inria - Renault) & 2013 (Inria - Berkeley)*

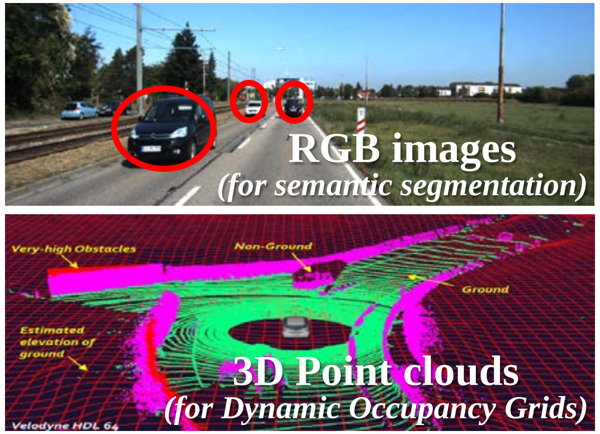


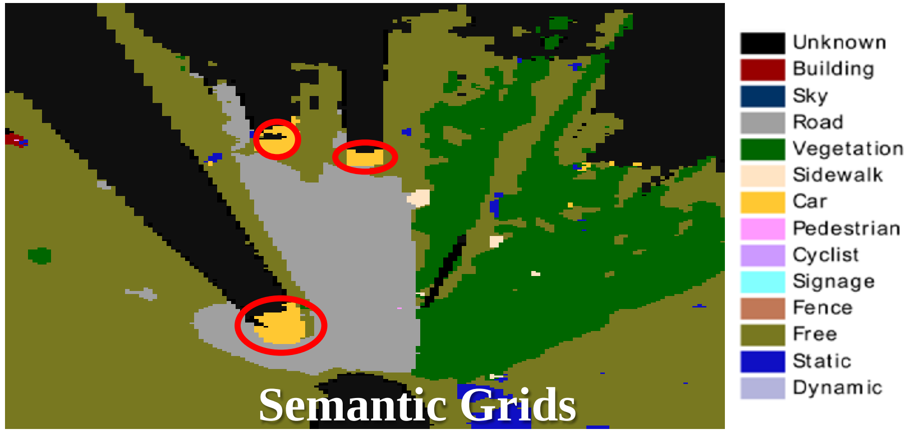
Human-like reasoning

Cooperation still on-going (R&D contracts + PhD)

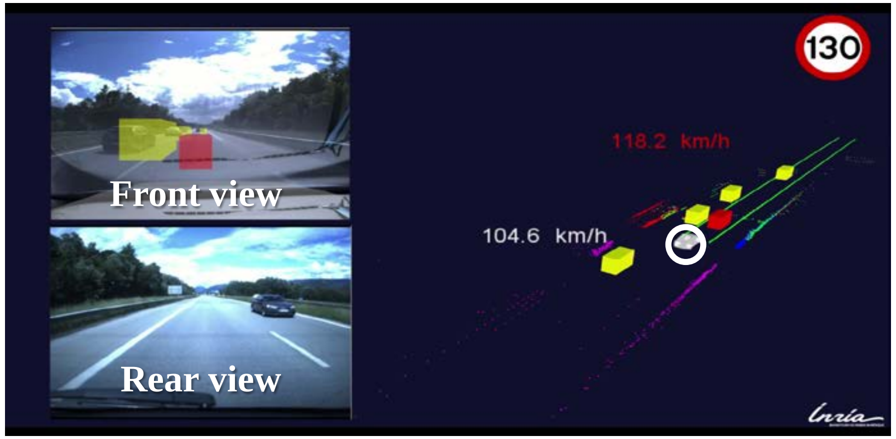
3rd *Paradigm:* Models improvements using Machine Learning

- **Perception level:** ***Construct "Semantic Grids" using Bayesian Perception & DL***





- **Decision-making level:** ***Learn driving skills for Autonomous Driving***
  - *1st Step:* ***Modeling Driver Behavior*** *using Inverse Reinforcement Learning (IRL)*
  - *2nd Step:* ***Predict motions*** *of surrounding vehicles &* ***Make Driving Decisions*** *for Ego Vehicle*



Perception Level: Semantic Grids (Bayesian Perception + DL)

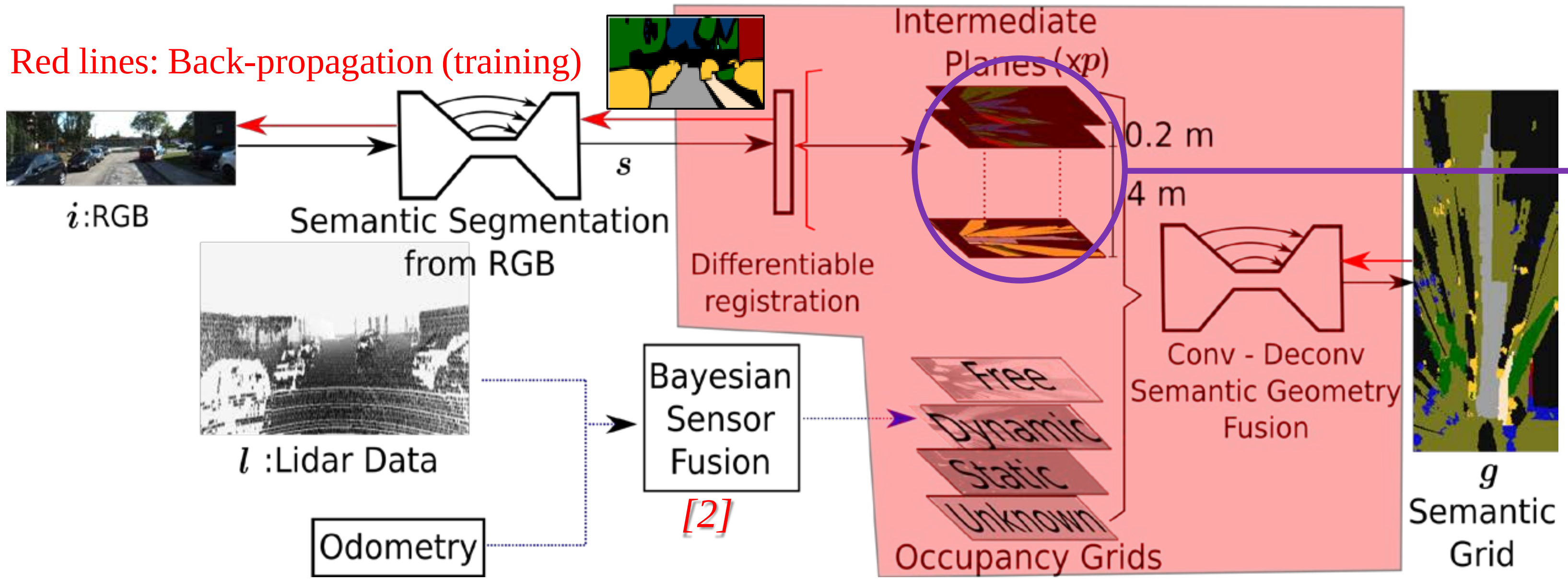
Objective: *Add **Semantic information** (cars, pedestrians, roads, buildings…) in each cell of the Dynamic Occupancy Grid model, by exploiting **additional RGB inputs***

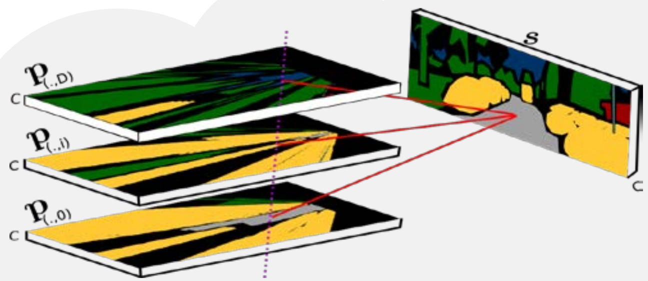
Approach: *A new **"Hybrid Sensor Fusion approach"** combining **Bayesian Perception & Deep Learning***

[1] [2] + Patent 2019 (Inria, Toyota)

Semantic Grid Network *[1] [3]*

Red lines: Back-propagation (training)





Intermediate layers (~20 layers)

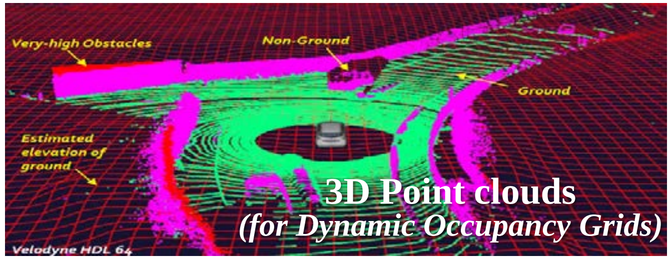
=> Learns the approximate heights of the classes/objects

=> No 3D reconstruction required & Less sensitive to calibration errors (initial camera/3D points calibration)

Implementation: Segnet Cuda/GPU + Kitti dataset

[1] Semantic grid estimation with a Hybrid Bayesian and Deep Neural Network approach, 0. Erkent et al., IEEE IROS 2018
[2] Conditional Monte Carlo Dense Occupancy Tracker, Rummelhard et al., ITSC 2015
[3] Segnet: A deep convolutional encoder-decoder architecture for image segmentation, Badrinarayanan et al., IEEE PAMI 39(12) 2017

Semantic Grids – *Experimental Evaluation Approach*



3D Point clouds
(for Dynamic Occupancy Grids)

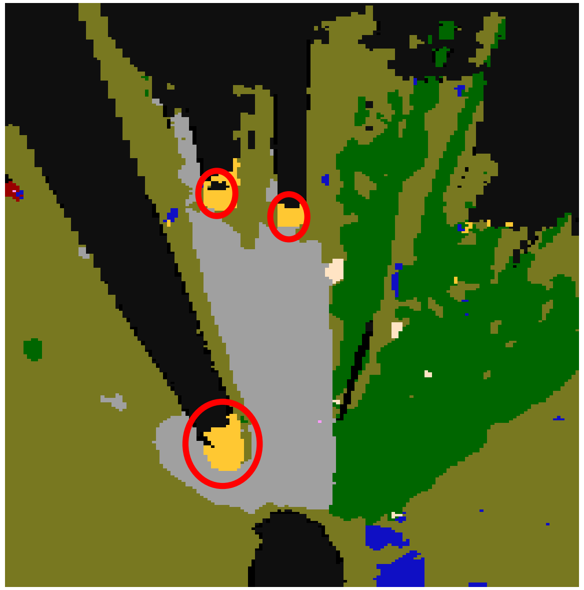
Frontal View *(RGB camera)*

Hybrid Sensor Fusion approach (Semantic Grid construction)

Frontal View Ground-Truth
=> labelled by humans in training datasets

Bird's Eye View Ground-Truth
*=> Frontal View GT **"projected" using Point-Cloud (Bayesian Perception)***
=> Densified by humans (point-clouds and images have different resolutions)

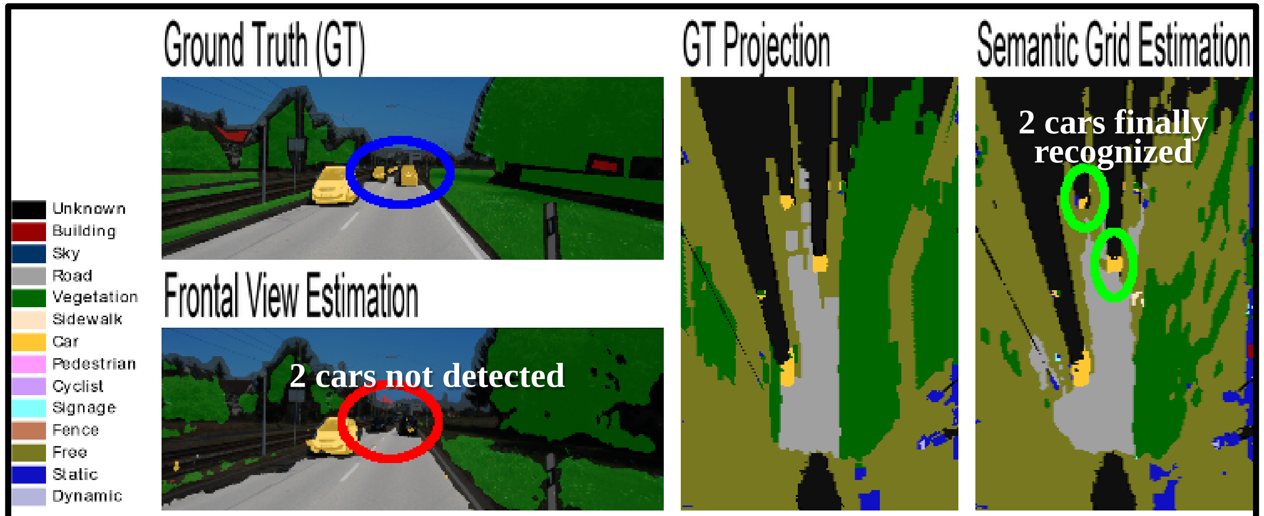
Comparison



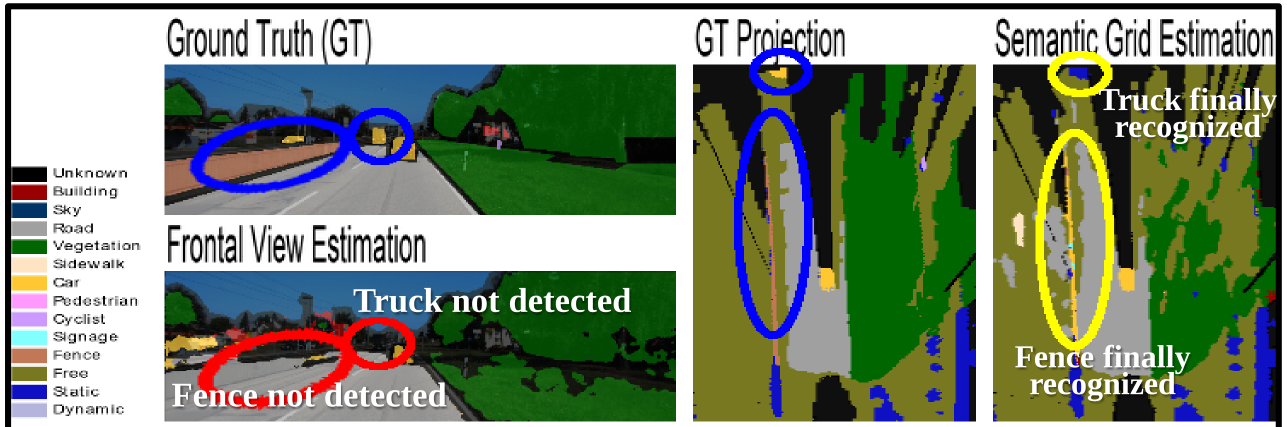
Semantic Grid Prediction
=> Dense structure obtained using hybrid integration

Labels

Semantic Grids – *Experimental Results*



2 cars not detected in frontal view estimation *(semantic segmentation)* … but recognized in semantic grid *(with the help of Dynamic Occupancy Grid)*



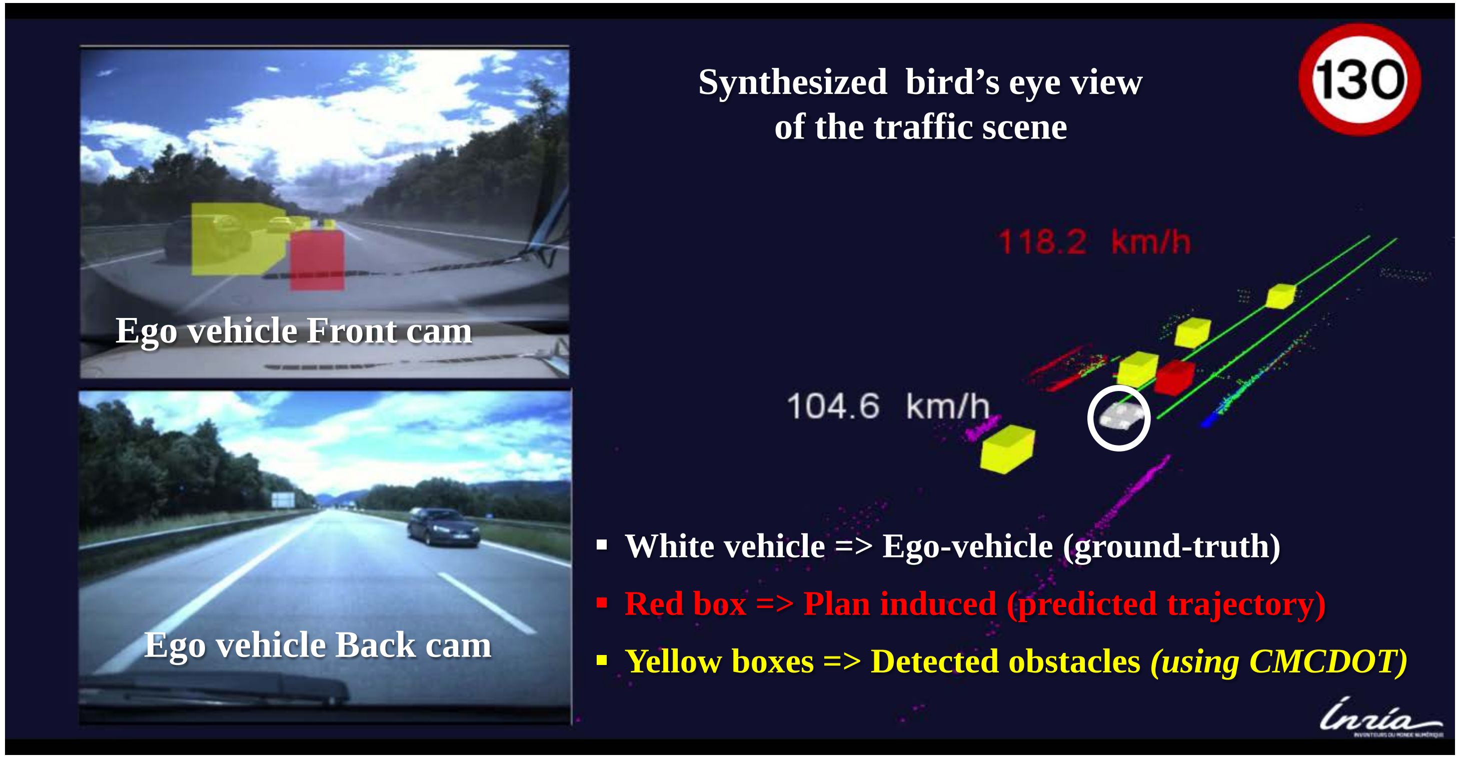
- **Fence** not detected in frontal view estimation …but recognized as an obstacle in semantic grid *(with the help of Dynamic Occupancy Grid)*
- **Truck** not detected in frontal view estimation … but recognized in semantic grid *(with the help of Dynamic Occupancy Grid)*

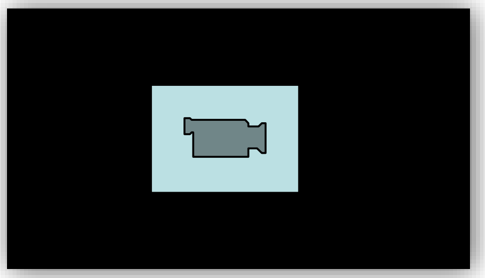
Decision-making level: Learning Driving Skills for AD
1st Step: Driver behavior modeling

- **Learn Model parameters** from real driving demonstrations using ***Inverse Reinforcement Learning (IRL)***
- **Driver behaviors** are modelled using a **Cost function** $\mathcal{C}(s) = \sum_{i=1}^{K} w_i \cdot f_i(s)$ which is assumed linear on a **set of K hand-crafted features** *(e.g. Lane index preferences, Deviation from desired velocity, TTC to frontal targets, Time-gap to rear targets …)*
- A **training set containing *"interesting highway vehicle interactions"*** *has been first constructed using our **Lexus vehicle***

=> Obtained models can be leverage to **Predict human driver behaviors & Generate human-like plans for the ego vehicle** *(mandatory in mixed traffic)*

[Sierra Gonzalez et al, ICRA 2018]



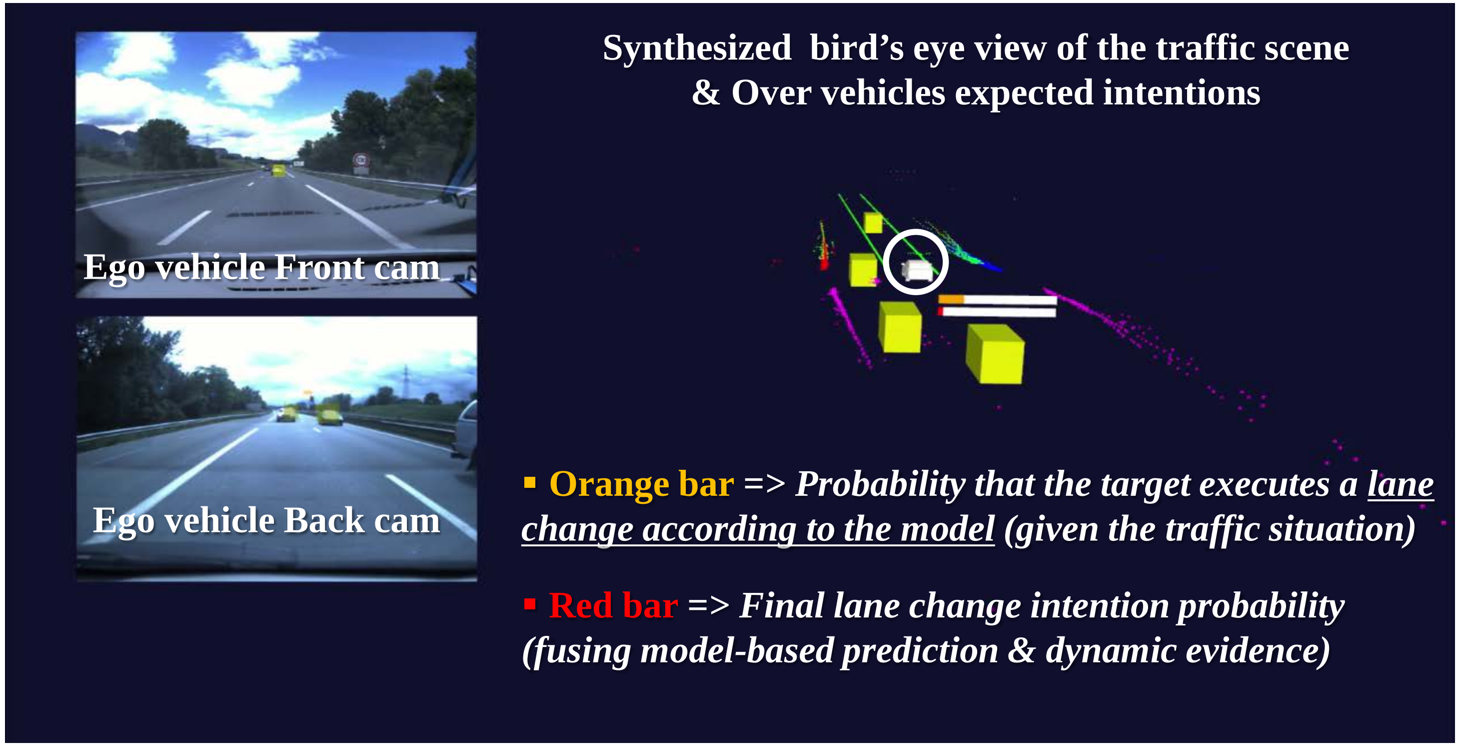


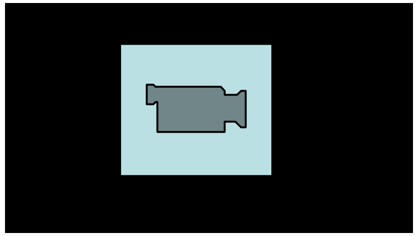
Comparison between demonstrated behavior in test set & behavior induced by the learned model

Decision-making level: Learning Driving Skills for AD
2nd Step: Motion Prediction & Driving Decisions

- A **realistic Human-like Driver Model** can be exploited to **Predict the long-term evolution** (10s and beyond) of traffic scenes *[Sierra Gonzalez et al., ITSC 2016]*
- For the **short/mid-term**, both the **Driver model** and the **Dynamics of the target** provide useful information to **determine future driving behaviors**

=> Our **probabilistic model fuses** ***Model-based Predictions & Dynamic evidence*** to produce robust **lane change intention estimations** in highway scenes *[Sierra Gonzalez et al., ICRA 2017]*





Comparison between demonstrated behaviors in test set & behaviors induced by the learned model & dynamics evidence

Summary & On going work

❑ Autonomous Driving in various Traffic & Context situations *(cooperation with industry)*

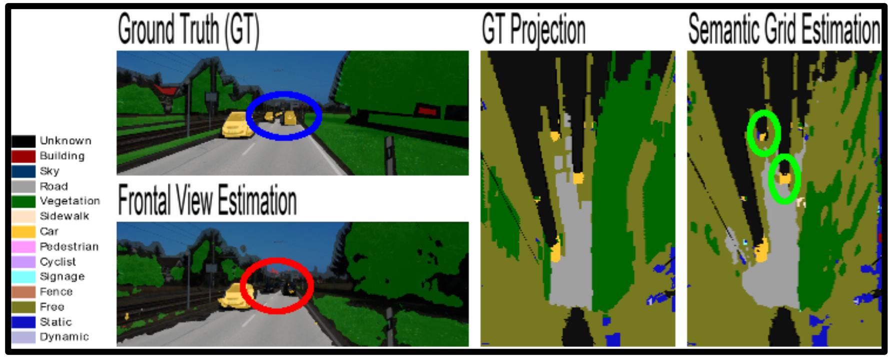
Autonomous Shuttles
(~15 km/h, Urban traffic)

Autonomous Bus (Iveco)
(up to 70 km/h, Urban traffic)

Autonomous Renault Zoe
(up to 70 km/h, Urban traffic)

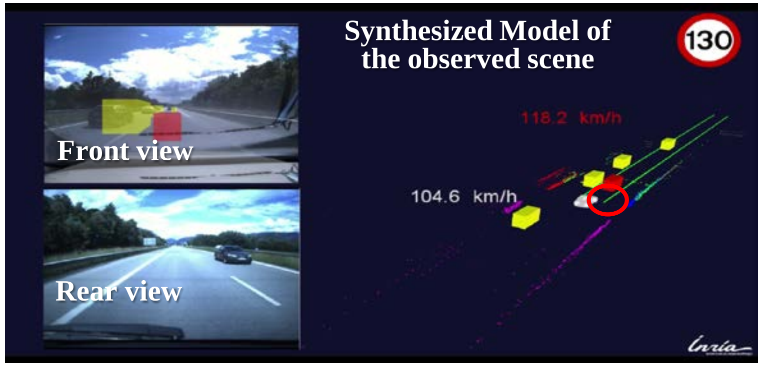
- Various Dynamics & Motion constraints & Contexts
- Adapted “Collision Risk” & “Collision avoidance maneuvers” (Risk & Maneuver characterization)
- **Cooperation IRT Nanoelec, Renault, Iveco …**

❑ Embedded & Extended “Semantic Grids” *(to improve scene understanding & decision-making)*

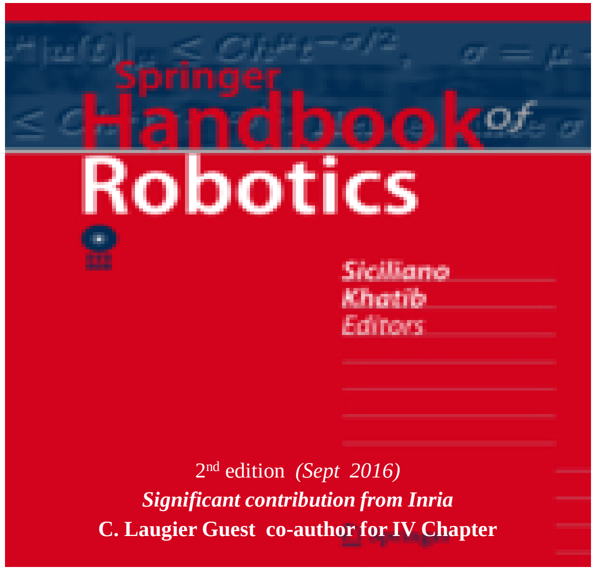


- Embedded “Semantic Grids” & “Panoptic Segmentation”
- Improved scene understanding (various weather conditions)
- **Cooperation Toyota**
- *1 Patent & 3 publications (IROS’18, ICARCV’18, Unmanned System journal 2019)*

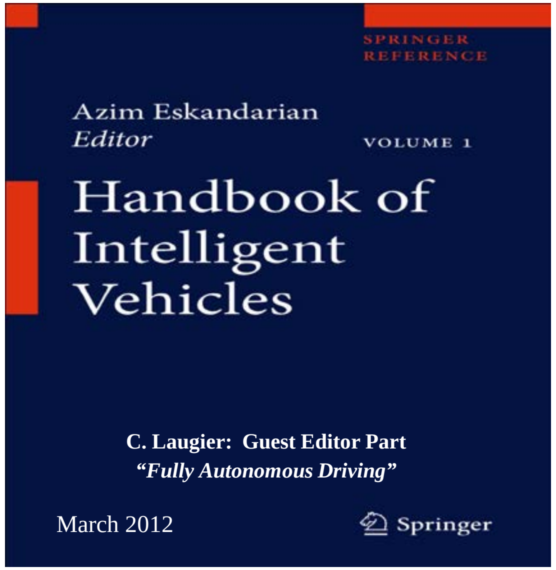
❑ Autonomous Driving in mixed traffic & Various traffic conditions (Prediction & Planning)



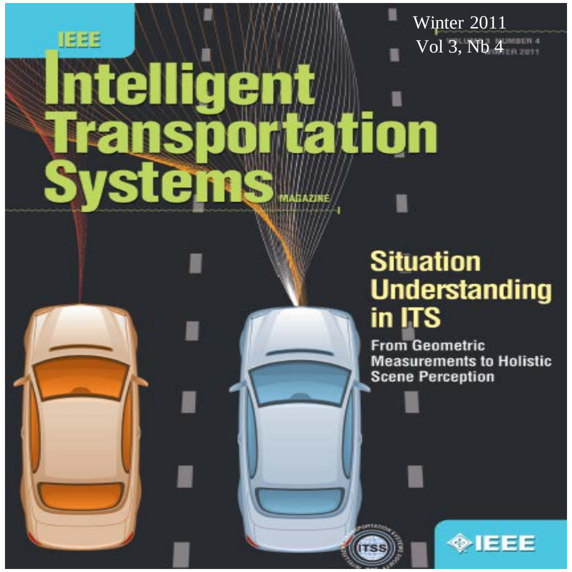
- **Driver Behavior modeling** using Driving dataset & Inverse Reinforcement Learning => ***Human-like Driver Model*** *(for mixed traffic)*
- **Motion Prediction & Driving Decision-making for AD** performed *by combining “learned Driver models” & “Dynamic evidences”*
- **Cooperation Toyota**
- *2 Patents & 3 publications (ITSC 2016, ICRA 2017, ICRA 2018) & PhD Thesis 2019*



2[nd] edition *(Sept 2016)*
Significant contribution from Inria
C. Laugier Guest co-author for IV Chapter



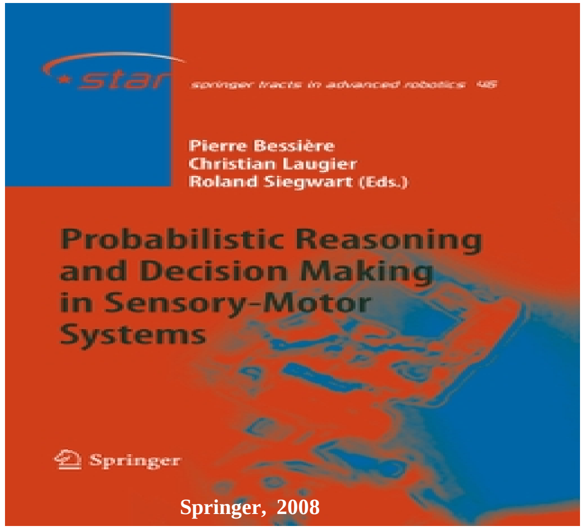
C. Laugier: Guest Editor Part
"Fully Autonomous Driving"
March 2012



Winter 2011
Vol 3, Nb 4

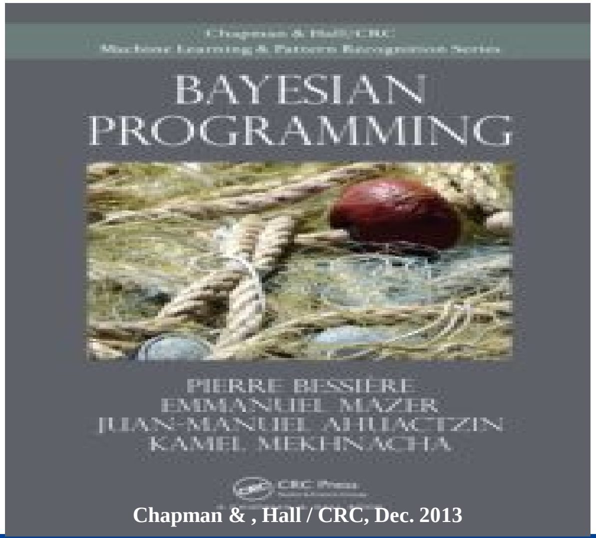
July 2013
Guest Editors:
C. Laugier & J. Machan

Thank You



Springer, 2008

IEEE RAS Technical Committee on "AGV & ITS"
=> Numerous Workshops & Special issues since 2002
=> Membership open !!



Chapman & , Hall / CRC, Dec. 2013

NANOELEC Inria